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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H02M 3/337, 1/00, B60L 1/00

A1

(11) International Publication Number: WO 95/34937

(43) International Publication Date: 21 December 1995 (21.12.95)

(21) International Application Number: PCT/US95/07078

(22) International Filing Date: 1 June 1995 (01.06.95)

(30) Priority Data:
08/258,142 10 June 1994 (10.06.94) US

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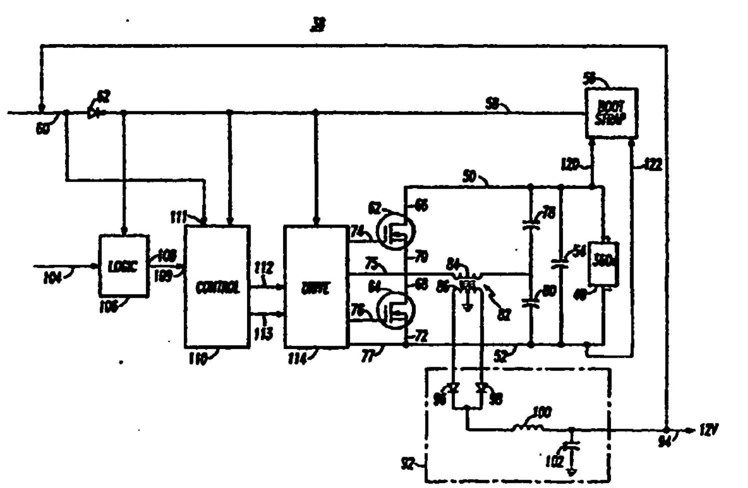
(81) Designated States: CA, CN, JP, KR, MX, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: AUTOMOTIVE 12-VOLT SYSTEM FOR ELECTRIC VEHICLES



(57) Abstract

An electric vehicle voltage converter (38) for a vehicle having a battery (40) supplying a battery voltage at a pair of terminals and a method for converting power from an electric vehicle propulsion system battery from a first voltage to a lower second voltage at a rate up to a maximum rated current. The converter (38) and the method operate by alternatingly supplying current from the battery (40) at the first voltage in first and second directions through a series connection of a transformer primary winding (84) and a capacitor (80), simultaneously drawing the maximum rated current at the second voltage from a secondary winding (86) of the transformer (82), and substantially fully charging the capacitor (80) when current is supplied through the primary winding in the first direction and substantially fully discharging the capacitor (80) when current is supplied through the primary winding in the second direction.

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AUTOMOTIVE 12-VOLT SYSTEM FOR ELECTRIC VEHICLES

RELATED APPLICATIONS

The following identified U.S. patent applications are filed on the same date as the instant application and are relied upon and incorporated by reference in this application.

U.S. patent application entitled "Flat Topping Concept" bearing attorney docket No. 58,295, and filed on the same date herewith;

U.S. patent application entitled "Electric Induction Motor And Related Method Of Cooling" bearing attorney docket No. 58,332, and filed on the same date herewith;

U.S. patent application entitled "Direct Cooled Switching Module For Electric Vehicle Propulsion System" bearing attorney docket No. 58,334, and filed on the same date herewith;

U.S. patent application entitled "Electric Vehicle Propulsion System" bearing attorney docket No. 58,335, and filed on the same date herewith;

U.S. patent application entitled "Speed Control and Bootstrap Technique For High Voltage Motor Control" bearing attorney docket No. 58,336, and filed on the same date herewith;

U.S. patent application entitled "Vector Control Board For An Electric Vehicle Propulsion System Motor Controller" bearing attorney docket No. 58,337, and filed on the same date herewith;

U.S. patent application entitled "Digital Pulse Width Modulator With Integrated Test And Control" bearing attorney docket No. 58,338, and filed on the same date herewith;

U.S. patent application entitled "Control Mechanism For Electric Vehicle" bearing attorney docket No. 58,339, and filed on the same date herewith;

U.S. patent application entitled "Improved EMI Filter Topology for Power Inverters" bearing attorney docket No. 58,340, and filed on the same date herewith;

U.S. patent application entitled "Fault Detection Circuit For Sensing Leakage Currents Between Power Source And Chassis" bearing attorney docket No. 58,341, and filed on the same date herewith;

U.S. patent application entitled "Electric Vehicle Relay Assembly" bearing attorney docket No. 58,342, and filed on the same date herewith;

U.S. patent application entitled "Three Phase Power Bridge Assembly" bearing attorney docket No. 58,343, and filed on the same date herewith;

U.S. patent application entitled "Electric Vehicle Propulsion System Power Bridge With Built-In-Test" bearing attorney docket No. 58,344, and filed on the same date herewith;

U.S. patent application entitled "Method For Testing A Power Bridge For An Electric Vehicle Propulsion System" bearing attorney docket No. 58,345, and filed on the same date herewith;

U.S. patent application entitled "Electric Vehicle Power Distribution Module" bearing attorney docket No. 58,346, and filed on the same date herewith;

U.S. patent application entitled "Electric Vehicle Chassis Controller" bearing attorney docket No. 58,347, and filed on the same date herewith;

U.S. patent application entitled "Electric Vehicle System Control Unit Housing" bearing attorney docket No. 58,348, and filed on the same date herewith;

U.S. patent application entitled "Low Cost Fluid Cooled Housing For Electric Vehicle System Control Unit" bearing attorney docket No. 58,349, and filed on the same date herewith;

U.S. patent application entitled "Electric Vehicle Coolant Pump Assembly" bearing attorney docket No. 58,350, and filed on the same date herewith;

U.S. patent application entitled "Heat Dissipating Transformer Coil" bearing attorney docket No. 58,351, and filed on the same date herewith; and

U.S. patent application entitled "Electric Vehicle Battery Charger" bearing attorney docket No. 58,352, and filed on the same date herewith.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to an electric vehicle and, more particularly, to a method and apparatus for providing automotive 12-volt electrical power from an electric vehicle battery. While the invention is subject to a wide range of applications, it is especially suited for use in electric vehicles that utilize batteries or a combination of batteries and other sources, e.g., a heat engine coupled to an alternator, as a source of power, and will be more particularly described in that connection.

Discussion of the Related Art

The internal combustion vehicle has long supplied an important share of the world's transportation needs. However, it is inevitable that petroleum reserves which supply fuel for the global internal combustion vehicle fleet will sooner or later decline to a point where the cost of fuel for internal combustion vehicles becomes unacceptable. Another factor clouding the future of internal combustion vehicles is the ever more stringent regulation of exhaust emissions from such vehicles. These and other factors have led to increasing efforts to develop a commercially viable alternative to the internal combustion vehicle which uses an electric propulsion system.

For an electric vehicle to be commercially viable, its costs and performance should be competitive with that of its internal combustion counterparts. Moreover, an electric vehicle must be reasonably compatible with existing internal combustion vehicles so that potential customers will find a comfortable and familiar environment within the electric vehicle.

Conventional vehicles include an incredible array of relatively inexpensive accessories that operate from a 12-volt power source. These accessories include radios, CD players, headlights, clocks, fan motors, windshield wipers, telephones, two-way communications radios, plug-in options, and others. The electric vehicle must therefore provide a 12-volt system for operation of such accessories. This 12-volt system must be provided in addition to the high-voltage (200-600 volt) system from which the electric vehicle propulsion system operates.

It has been proposed to provide the electric vehicle with a 12-volt electrical system identical to the system of conventional internal combustion vehicles, including a 12-volt battery, and to recharge the 12-volt battery when the high voltage batteries recharge. However, this proposal is not practical because the electronic components of the vehicle propulsion system require 12-volt power to operate and the loading upon the 12-volt system is thus unpredictable. For example, the headlights may or may not be on, the fan or windshield wipers may or may not be in use, or the vehicle may be at rest with no load upon the high voltage system while the 12-volt system is heavily loaded. Another solution for providing a 12-volt system in an electric vehicle is to employ a small 12-volt battery charger that operates from the high voltage battery, thereby maintaining charge on the 12-volt battery. This proposal is also unacceptable, however, again because of the high variable load which can exist on the 12-volt system. Uncertainty surrounding the timing and extent of load upon the 12-volt system means that a 12-volt battery charger operating from the high voltage battery must be capable of sustaining at least the maximum continuous load expected. This changes the requirement from a small battery charger to a full equivalent of the conventional internal combustion vehicle alternator.

The considerations noted above indicate that a 12-volt battery is not necessarily an essential component of a

12-volt electrical system. The main function of a large 12-volt storage battery in internal combustion vehicles is to provide power for starting the engine. Since electric vehicles do not require "starting" in the same manner as internal combustion engines, a large 12-volt storage battery can be omitted if a DC/DC converter can be provided which supplies not only the continuous load of the 12-volt electrical system, but also the peak loading.

In order to satisfy the requirements of a 12-volt electrical system for an electric vehicle, a DC/DC converter must be provided which provides a 12-volt regulated output. The converter must be not only inexpensive but must maintain regulation in the face of widely varying loading requirements of, for example, no load to 100 amperes. In order to prevent undesirable discharge of the high voltage battery or damage to components of the vehicle's electrical system, the DC/DC converter must provide current limiting beginning at approximately 100 amps. Moreover, the converter must provide a regulated 12-volt output in the face of a widely varying input voltage of, for example, 230 volts to over 400 volts. A further requirement is that the output of the system must be galvanically isolated from the high voltage battery to provide for a safe operation. Existing apparatus and methods fail to meet the requirements set forth above.

SUMMARY OF THE INVENTION

Accordingly, the present invention is directed to methods and apparatus for providing a 12-volt electrical system in an electric vehicle that substantially obviates one or more of the problems caused by limitations and advantages of the related art.

Features and advantages of the invention will be set forth in the description which follows, and in part will be apparent from the description, or may be learned by practice of the invention. The objectives and other advantages of the invention will be realized and attained by the method and apparatus particularly pointed out in the

written description and claims of the present application, as well as the appended drawings.

To achieve these and other advantages in accordance with the purpose of the invention, as embodied and broadly described, the invention provides an electric vehicle voltage converter for a vehicle having a battery supplying a battery voltage at a pair of terminals. The converter provides DC output current up to a maximum rated current at a voltage below the battery voltage. The converter includes first and second input power conductors for coupling to the battery terminals. First and second electronic switching devices are provided, each comprising a control terminal and first and second switching terminals. The first switching terminal of the first electronic switching device is coupled to the first input power conductor and the second switching terminal of the second electronic switching device is coupled to the second input power conductor. The second switching terminal of the first electronic switching device is coupled to the first switching terminal of the second electronic switching device.

The converter further includes a first capacitor having a first capacitance and first and second capacitor terminals, the second capacitor terminal being coupled to the second input power conductor. An output transformer having a primary winding including first and second primary terminals and a secondary winding is provided. The first primary terminal is coupled to the second switching terminal of the first electronic switching device and the first switching terminal of the second electronic switching device. The second primary terminal is coupled to the first capacitor terminal. The converter further includes an output rectifier circuit coupled to the secondary winding and having an output terminal providing DC output current.

Finally, a control circuit is provided which is coupled to the control terminals of the first and second electronic switching devices for activating the control terminals to alternatingly switch the first and second

electronic switching devices at a variable rate in accordance with output current demanded from the secondary winding to alternatingly supply current to and withdraw current from the first capacitor. The first capacitance has a value such that the first capacitor is substantially fully charged and substantially fully discharged when the control circuit operates the first and second electronic switching devices at a rate to deliver the maximum rated current.

In another aspect, the invention provides a method for converting power from an electric vehicle propulsion system battery from a first voltage to a lower second voltage at a rate up to a maximum rated current. The method comprises the steps of alternatingly supplying current from the battery at the first voltage in first and second directions through a series connection of a transformer primary winding and a capacitor, simultaneously drawing the maximum rated current at the second voltage from a secondary winding of the transformer, and substantially fully charging the capacitor when current is supplied through the primary winding in the first direction and substantially fully discharging the capacitor when current is supplied through the primary winding in the second direction.

It is to be understood that both the forgoing general description and the following detailed description are exemplary and explanatory, and are intended to provide explanation of the invention as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification, illustrate a presently preferred embodiment of the invention and, together with the descriptions, serve to explain the principles of the invention. In the drawings:

Fig. 1 is a block diagram of an electric vehicle propulsion system in accordance with a preferred embodiment of the invention;

Fig. 2 is a power distribution diagram of the electric vehicle propulsion system of Fig. 1;

Fig. 3 is a functional diagram of the electric vehicle propulsion system of Fig. 1;

Fig. 4 is a diagram, partially schematic and partially in block form, of the DC/DC converter shown in Figs. 1-3;

Fig. 5 is an electrical schematic diagram of the bootstrap circuit shown in Fig. 4; and

Fig. 6 is an electrical schematic diagram of the gate drive circuit of Fig. 4.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Reference will now be made in detail to a present preferred embodiment of the invention, an example of which is illustrated in the accompanying drawings.

As shown in Fig. 1, there is provided in an electric vehicle propulsion system 10 comprising a system control unit 12, a motor assembly 24, a cooling system 32, a battery 40, and a DC/DC converter 38. The system control unit 12 includes a cold plate 14, a battery charger 16, a motor controller 18, a power distribution module 20, and a chassis controller 22. The motor assembly 24 includes a resolver 26, a motor 28, and a filter 30. The cooling system 32 includes an oil pump unit 34 and a radiator/fan 36.

Fig. 2 is a power distribution diagram of the electric vehicle propulsion system 10. As shown in Fig. 2, the battery 40 serves as the primary source of power for the electric propulsion system 10. The battery 40 comprises, for example, a sealed lead acid battery, a monopolar lithium metal sulfide battery, a bipolar lithium metal sulfide battery, or the like, for providing a 320 volt output. Preferably, the electric propulsion system 10 works over a wide voltage range, e.g., 120 volts to 400 volts, to accommodate changes in the output voltage of the battery 40 due to load or depth of discharge. However, the electric

vehicle propulsion system 10 is preferably optimized for nominal battery voltages of about 320 volts.

The power distribution module 20 is coupled to the output of the battery 40 and includes, among other things, fuses, wiring, and connectors for distributing the 320 volt output from the battery 40 to various components of the electric vehicle propulsion system 10. For example, the power distribution module 20 distributes the 320 volt output from the battery 40 to the motor controller 18, the DC/DC converter 38, the oil pump unit 34, and the battery charger 16. The power distribution module 20 also distributes the 320 volt output from the battery 40 to various vehicle accessories, which are external to the electric vehicle propulsion system 10. These vehicle accessories include, for example, an air conditioning system, a heating system, a power steering system, and any other accessories that may require a 320 volt power supply. Additional details concerning the power distribution module 20 are disclosed in copending U.S. Patent Application Serial No. __________ (Westinghouse Case No. 58,346) entitled "ELECTRIC VEHICLE POWER DISTRIBUTION MODULE" filed on the same day as this application.

The DC/DC converter 38, which, as described above, is coupled to the 320 volt output of the power distribution module 20, converts the 320 volt output of the power distribution module 20 to 12 volts. The DC/DC converter 38 then supplies its 12-volt output as operating power to the battery charger 16, the motor controller 18, the chassis controller 22, the oil pump unit 34, and the radiator/fan 36. The DC/DC converter 38 also supplies its 12-volt output as operating power to various vehicle accessories, which are external to the electric vehicle propulsion system 10. These vehicle accessories include, for example, vehicle lighting, an audio system, and any other accessories that may require a 12-volt power supply. It should be appreciated that the DC/DC converter 38 eliminates the need for a separate 12-volt storage battery. Additional details concerning the DC/DC

converter 38 are disclosed in copending U.S. Patent Application Serial No. __________ (Westinghouse Case No. 58,351) entitled "HEAT DISSIPATING TRANSFORMER COIL" filed on the same day as this application.

As shown in Fig. 3, the components of the electric vehicle propulsion system 10 are interconnected via various data busses. The data busses can be of the electrical, optical, or electro-optical type as is known in the art.

The battery charger 16 receives command signals from and sends status signals to the motor controller 18 for charging the battery 40. The battery charger 16 provides a controlled battery charging current from an external AC power source (not shown in Fig. 3).

Referring now to Fig. 4, there is shown a diagram of the DC/DC converter 38 of Figs. 1-3 connected to the battery 40, which supplies 320 volts of DC at its plus and minus terminals. The converter 38 includes a pair of input power conductors 50 and 52 which are coupled to the terminals of the battery 40. A capacitor 54, preferably a metalized polypropylene capacitor, is connected across conductors 50 and 52. The function of the capacitor 54 is to filter out high frequency components. A bootstrap power supply circuit 56 is also connected across the input power conductors 50 and 52. The bootstrap power supply circuit 56 provides start-up operating power at an output terminal 58 for remaining components of the converter 38. This is required because the converter 38 is the sole source of 12-volt operating power for all components in the entire electric vehicle system 10.

The converter 38 includes a 12-volt input terminal 60 from which converter 38 draws operating power during conditions other than initial start-up. A diode 62 is connected between the input terminal 60 and the bootstrap output terminal 58 to block the flow of operating power from the bootstrap power supply circuit 56 to the remainder of the vehicle 12-volt system.

The converter 38 includes a pair of electronic switch devices 62 and 64. In the preferred embodiment, the

switching devices 62 and 64 each include a type IXTN36N60 high voltage switching field effect transistor (FET) commercially available from the IXYS Corporation of San Jose, California. The voltage rating of switching devices 60 and 62, in the preferred embodiment, is 600 volts and the current rating is 36 amperes. Devices 62 and 64 include a first switching terminal 66, 68, respectively, and a second switching terminal 70, 72, respectively. The switching devices 62 and 64 each include a control terminal 74, 76, respectively. The switching terminal 66 is connected to the first input power conductor 50 and the switching terminal 72 is connected to the second input power conductor 52.

The converter 38 includes capacitors 78 and 80 connected in series across the input conductors 50 and 52. The converter 38 further includes an output transformer 82 having a primary winding 84 and a secondary winding 86. The primary winding 84 is connected between the junction of capacitors 78 and 80 and the junction of switching terminals 68 and 70.

In the preferred embodiment, the output transformer 82 comprises a step-down transformer with a 6:1 turns ratio. The primary winding 84 includes 18 turns of 0.005 inch thick by 1.90 inch wide copper foil, which is slightly smaller than an equivalent AWG-9 wire size, wound upon a core having a shape of two "E's" and an initial permeability of 2500 at 25°C. The secondary winding 86 includes a center tap 88 connected to a circuit common connection 90. Each portion of the secondary winding 86 includes three turns.

In the preferred embodiment, the capacitor 54 comprises a 2.2 microfarad metalized polypropylene capacitor. In the preferred embodiment, the capacitors 78 and 80 each comprise three 0.1 microfarad metalized polypropylene capacitors connected in parallel.

The secondary winding 86 is connected to an output rectifier circuit 92. The output rectifier circuit 92 includes an output terminal 94 which provides 12-volt DC output current at a maximum rated current of 100 amperes in

the preferred embodiment. The rectifier circuit 92 includes a pair of diodes 96 and 98 having respective anodes connected to opposite ends of the secondary winding 86 and cathodes connected together and to a first terminal of an output inductor 100. The other terminal of the inductor 100 is connected to the output terminal 94 and to an output capacitor 102. The other end of the capacitor 102 is connected to the circuit common connection. In the preferred embodiment, the output inductor 100 comprises a 5 microhenry inductor and the output capacitor 102 comprises a pair of 1800 microfarad aluminum electrolytic capacitors connected in parallel.

The converter 38 includes an enable terminal 104 for receiving an enable signal from a Battery Energy Management System (BEMS) generated on the motor controller 18. The enable input terminal 104 is connected to a logic circuit 106, the output 108 of which is connected to an enable terminal 109 of a control circuit 110. Control circuit 110 includes a voltage sense input terminal 111 connected to the input terminal 60. An output terminal 112 of the control circuit 110 is supplied to a drive circuit 114.

The converter 38 functions as an inverter circuit in which switching devices 62 and 64 are alternatingly switched on and off to conduct current from the input conductors 50 and 52 through the primary winding 84 of the transformer 82. This action induces current through the secondary winding 86 which is rectified by the diodes 96 and 98 and filtered by the inductor 100 and capacitor 102 to provide regulated 12-volt DC output power at the output terminal 94 up to a maximum rated current of 100 amperes.

Preferably, the control circuit 110 comprises a resonant control circuit. In the preferred embodiment, control circuit 110 comprises a type UC2860DW resonant inverter control chip commercially available from the Unitrode Integrated Circuits Corporation of Merrimack, New Hampshire.

Fig. 5 shows an electrical schematic diagram of the bootstrap circuit 56. The bootstrap circuit 56 includes a pair of input terminals 120, 122 respectively connected to the input power conductors 50 and 52 of the converter 38. The bootstrap circuit 56 includes a transformer having a primary winding 124 and secondary windings 126, 128, 130, and 132. The bootstrap circuit 56 also includes a pair of switching field effect transistors (FETs) 134 and 136. The bootstrap power supply circuit 56 also includes a cutoff circuit comprising an FET 138. Resistors 140 and a zener diode 142 are connected in series across the input terminals 120 and 122. A control terminal of FET 138 is connected to the junction of the resistors 140 and the zener diode 142. Current flow through the resistors 140 and the zener diode 142 turns on the FET 138 when conductors 120 and 122 are initially connected to the battery 40.

Switching terminals of the FET 134 are connected in series with the primary winding 124 and a capacitor 144. By action of resistors 146 connected to a control terminal of the FET 134, FET 134 is rendered conductive such that current flows from the input conductor 120 through the switching terminals of the FET 134, the primary winding 124, the capacitor 144, and the switching terminals of the FET 138 to the input terminal 122.

Current flow through the primary winding 124 induces current flow in the secondary winding 128, which tends to render the FET 134 even more conductive. Thus, more current flows through the primary winding 124. At the same time, current is induced in the opposite direction in the secondary winding 126, thus tending to render the FET 136 nonconductive.

Current continues to increase through the primary winding 124 and charging capacitor 144. However, before the capacitor 144 is fully charged, the primary winding 124 saturates. Once it saturates, the magnetic field induced by the primary winding 124 begins to collapse, reversing the current flow through the secondary winding 128. This tends

to render the FET 134 nonconductive. At the same time, current flow is reversed through the secondary winding 126, which tends to render the FET 136 conductive. The capacitor 144 then discharges through the primary winding 124 to reinforce the nonconductive state of the FET 134 and the conductive state of the FET 136. This action continues until the primary winding 124 again saturates, resulting once again in reversal of the conductivity states of the FETs 134 and 136.

Current flow in alternate directions through the primary winding 124 also induces alternating current flow through the secondary windings 130 and 132. This current is rectified by diodes 148 and 150, filtered by a capacitor 152 and limited by a zener diode 154 to render a 12-volt DC output upon the bootstrap output terminal 58.

As seen in Fig. 5, the bootstrap supply circuit includes a detector circuit comprising a comparator 160. The comparator 160 has a first terminal connected through the diode 62 to the input power terminal 60 and a second terminal coupled to the circuit common connection 90. An output of the comparator 160 is connected to an optoisolator 162 connected across the control terminal of the FET 138. When the voltage of the externally supplied operating power appearing on the input terminal 60 rises above a predetermined value (in the preferred embodiment, 10 volts) the comparator 160 activates the optoisolator 162 thereby rendering the FET 138 nonconductive. The optoisolator 162 and FET 138 thus constitute a cutoff circuit for deactivating the bootstrap power supply.

Referring now to Fig. 6, there is shown a detailed electrical schematic diagram of the drive circuit 114. A pair of input terminals 160 and 162 are connected to the output terminals 112 and 113 of the control circuit 110. The input terminals 160 and 162 are connected through resistors 164 and 166 to the input of a dual gate drive circuit 168 which, in the preferred embodiment, comprises a type TC4427EOA dual gate drive integrated circuit manufactured by

the Teledyne Semiconductor Corporation of Mountain View, California. Output terminals 170 and 172 of the gate drive circuit 168 are connected through capacitors 174 and 176 to primary windings 178 and 180 of gate drive transformers 182 and 184. A secondary winding 186 of the gate drive transformer 182 is connected through a resistor 190 to output terminals 74 and 75 of the gate drive circuit 114. A protective device 192 comprising a pair of back-to-back connected zener diodes is connected across output terminals 74 and 75.

In a similar manner, the secondary winding 188 of gate drive transformer 184 is connected through a resister 194 to output terminals 76 and 77 of the gate drive circuit 114. A protective device 196 is connected across the output terminals 76 and 77.

The operation of the DC/DC converter 38 will now be described.

When 12-volt operating power for the converter 38 is initially supplied by the bootstrap circuit 56, as previously described, an enable signal received at the terminal 104 (Fig. 4) will cause the logic circuit 106 to generate an activating signal upon its output terminal 108. This activating signal is supplied to the enable terminal 109 of the control circuit 110. The control circuit 110 then generates variable-frequency output pulses over the output terminals 112 and 113 and supplies them to the drive circuit 114. These output pulses are supplied over terminals 74, 75, 76, and 77 to the FETs 62 and 64. This causes the FETs 62 and 64 to alternatingly switch between opposite conductive states as specified by the pulses generated by the control circuit 110. That is, when FET 62 is rendered conductive, FET 64 is rendered nonconductive and vice-versa.

In an initial condition, before operation of the FETs 62 and 64, capacitor 78 and 80 form a voltage divider across the input conductors 50 and 52. Thus, one half of the battery voltage appears across each of the capacitors 78 and 80. When the FET 62 is first rendered conductive, half of

the current through the FET 62 arrives from the battery 40 to charge the capacitor 80 and half comes from discharging the capacitor 78.

The FET 62 is then rendered nonconductive and FET 64 is rendered conductive. In this state, half of the current through the FET 64 comes from the discharge of the capacitor 80 and half comes from the battery 40 charging capacitor 78.

Switching of the FETs 62 and 64 causes current flow in alternating directions through the primary winding 84. This in turn induces current through the secondary winding 86 which is rectified by the diodes 96 and 98 and filtered by the inductor 100 and the capacitor 102 to provide 12-volt DC power at the output terminal 94.

At light loads, that is, when the current drawn from the output terminal 94 is low, capacitors 78 and 80 continue to act as a voltage divider. Thus, the voltage across the primary winding 84 is approximately one half of the battery voltage. As additional current is drawn from the output terminal 94, the voltage at the terminal 94 tends to decrease. This decrease in voltage is sensed at a voltage read terminal 111 of the control circuit 110.

The control circuit 110 increases the frequency of pulse signals delivered through the drive circuit 114 to the input terminals 74-77 of the FETs 62 and 64. This causes the FETs 62 and 64 to switch between conductive states at a faster rate. Current through the primary winding 84 then increases and the voltage at the junction of capacitor 78 and 80 begins to change according to the relationship $\Delta WV = \frac{I\Delta WT}{C}$. As more current enters the capacitors 78 and 80, the voltage across each of the capacitors increases. The voltage at the junction of the capacitors 78 and 80 increases when the FET 62 is rendered conductive and decreases when the FET 64 is rendered conductive. At this time, when either of the FETs 62 or 64 is rendered conductive, the voltage across

the primary winding 84 is also increased, thereby restoring the output voltage level at the output terminal 94.

At maximum rated load current, when the FET 62 is rendered conductive, the junction between the capacitors 78 and 80 reaches the full voltage of the battery 40. In this condition, the capacitor 78 is completely discharged and the capacitor 80 is completely charged. When the FET 62 is then rendered nonconductive and the FET 64 is rendered conductive, the full battery voltage is applied across the primary winding 84. Then, the voltage at the junction of capacitor 78 and 80 decreases to zero, as the capacitor 78 becomes completely charged and the capacitor 80 becomes completely discharged.

When the FET 62 is next rendered conductive, the full battery voltage will again be applied across the primary winding 84. If the load at the output terminal 94 is further increased, thus attempting to draw additional current above maximum rated current, the converter 38 will begin to limit the amount of current supplied at the output terminal 94 and permit the voltage at the output terminal 94 to fall.

In the preferred embodiment, the control circuit 110 comprises a resonant mode controller chip, even though the FETs 62 and 64 are not arranged in a resonant switching circuit. This permits more precise output voltage regulation to be achieved. Each FET 62 and 64 is rendered conductive for a specific length of time. The resonant mode controller chip is used to change the frequency at which the FETs 62 and 64 are rendered conductive and nonconductive. As the load at the output terminal 94 increases, the capacitors 78 and 80 become alternatingly fully charged and fully discharged during each cycle, thereby limiting the power transfer to the output terminal 94. To compensate, the control circuit 110 commands the FETs to operate more often, that is, at a higher frequency, up to a maximum frequency determined by the pulse width of the controller circuit 110. In the preferred embodiment, the maximum frequency is 33 kHz.

When only small amounts of current are drawn from the output terminal 94, FETs 62 and 64 are operated in a "hard switching" manner. That is, the wave form of current flow through the FETs 62 and 64 is essentially a square wave. As additional current is drawn from the output terminal 94, the capacitors 78 and 80 operate as reactive current limiters. Thus, the character of operation of the FETs 62 and 64 changes from hard switching to soft switching. At heavier loads, where hard switching losses are usually highest, the capacitors 78 and 80 are fully charged at the end of each cycle when the FETs 62 and 64 must be rendered nonconductive. The result is that no current is switched and there are no switching losses during that portion of the FETs operation. Switching losses are thus cut in half at high loads, and the efficiency of the switching circuit including FETs 62 and 64 increases under the conditions when high efficiency is most needed.

In an alternative embodiment, the total capacitance of capacitors 78 and 80 could be combined into a single capacitor 80, and capacitor 78 eliminated. However, under this configuration, twice the average current would be drawn from the battery 40 during half the time. This would increase the amount of current ripple in the circuit. Thus, it is preferred that the configuration of Fig. 4 be provided.

It should be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit or scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention, provided they come within the scope of the appended claims and their equivalents.

What is claimed:

1. An electric vehicle voltage converter for a vehicle having a battery supplying a battery voltage at a pair of terminals, the converter providing DC output current up to a maximum rated current at an output voltage below the battery voltage and comprising:

first and second input power conductors for coupling to the battery terminals;

first and second electronic switching devices each comprising a control terminal and first and second switching terminals, the first switching terminal of the first electronic switching device being coupled to the first power conductor, the second switching terminal of the second electronic switching device being coupled to the second power conductor, and the second switching terminal of the first electronic switching device being coupled to the first switching terminal of the second electronic switching device;

a first capacitor having a first capacitance and first and second capacitor terminals, the second capacitor terminal being coupled to the second input power conductor;

an output transformer having a primary winding comprising first and second primary terminals and a secondary winding, the first primary terminal being coupled to the second switching terminal of the first electronic switching device and the first switching terminal of the second electronic switching device, and the second primary terminal being coupled to the first capacitor terminal;

an output rectifier circuit coupled to the secondary winding and having an output terminal providing DC output current; and

a control circuit coupled to the control terminals of the first and second electronic switching devices for activating the control terminals to alternatingly switch the first and second electronic switching devices at a variable rate in accordance with output current demanded from the secondary winding to alternatingly supply charging current to

and withdraw charging current from the first capacitor, the first capacitance having a value such that the first capacitor is substantially fully charged and substantially fully discharged when the control circuit operates the first and second electronic switching devices at a rate to deliver the maximum rated current.

2. An electric vehicle voltage converter as recited in claim 1, further comprising a second capacitor having a second capacitance, a first terminal coupled to the first capacitor and the primary winding, and a second terminal coupled to the first input power conductor, the first and second capacitances having values such that the first and second capacitors are substantially fully charged and substantially fully discharged when the control circuit operates the switching devices at a rate to deliver the maximum rated current.

3. An electric vehicle voltage converter as recited in claim 1, wherein the control circuit comprises a resonant control circuit.

4. An electric vehicle voltage converter as recited in claim 1, further comprising:

a pair of drive transformers each coupled to one of the control terminals; and

a pair of drive circuits each coupled to the control circuit and to one of the drive transformers.

5. An electric vehicle voltage converter as recited in claim 1, further comprising a bootstrap power supply circuit coupled to the battery terminals for supplying start-up operating power to the control circuit.

6. An electric vehicle voltage converter as recited in claim 5, wherein the bootstrap power supply circuit comprises a bootstrap transformer having a primary

winding, a pair of switching field effect transistors, and an activation circuit for selectively operating the field effect transistors to alternatingly conduct current from the battery terminals through the bootstrap transformer primary winding.

7. An electric vehicle voltage converter as recited in claim 6, wherein:

the electric vehicle voltage converter comprises a power input terminal for receiving externally supplied operating power; and

the bootstrap power supply circuit comprises a cutoff circuit for deactivating the bootstrap power supply circuit, a detector circuit having an input coupled to the power input terminal, and an output coupled to the cutoff circuit for deactivating the bootstrap power supply when the externally supplied operating power is above a predetermined voltage level.

8. A method for converting power from an electric vehicle propulsion system battery from a first voltage to a lower second voltage, at a rate up to a maximum rated current, comprising the steps of:

alternatingly supplying current from the battery at the first voltage in first and second directions through a series connection of a transformer primary winding and a capacitor;

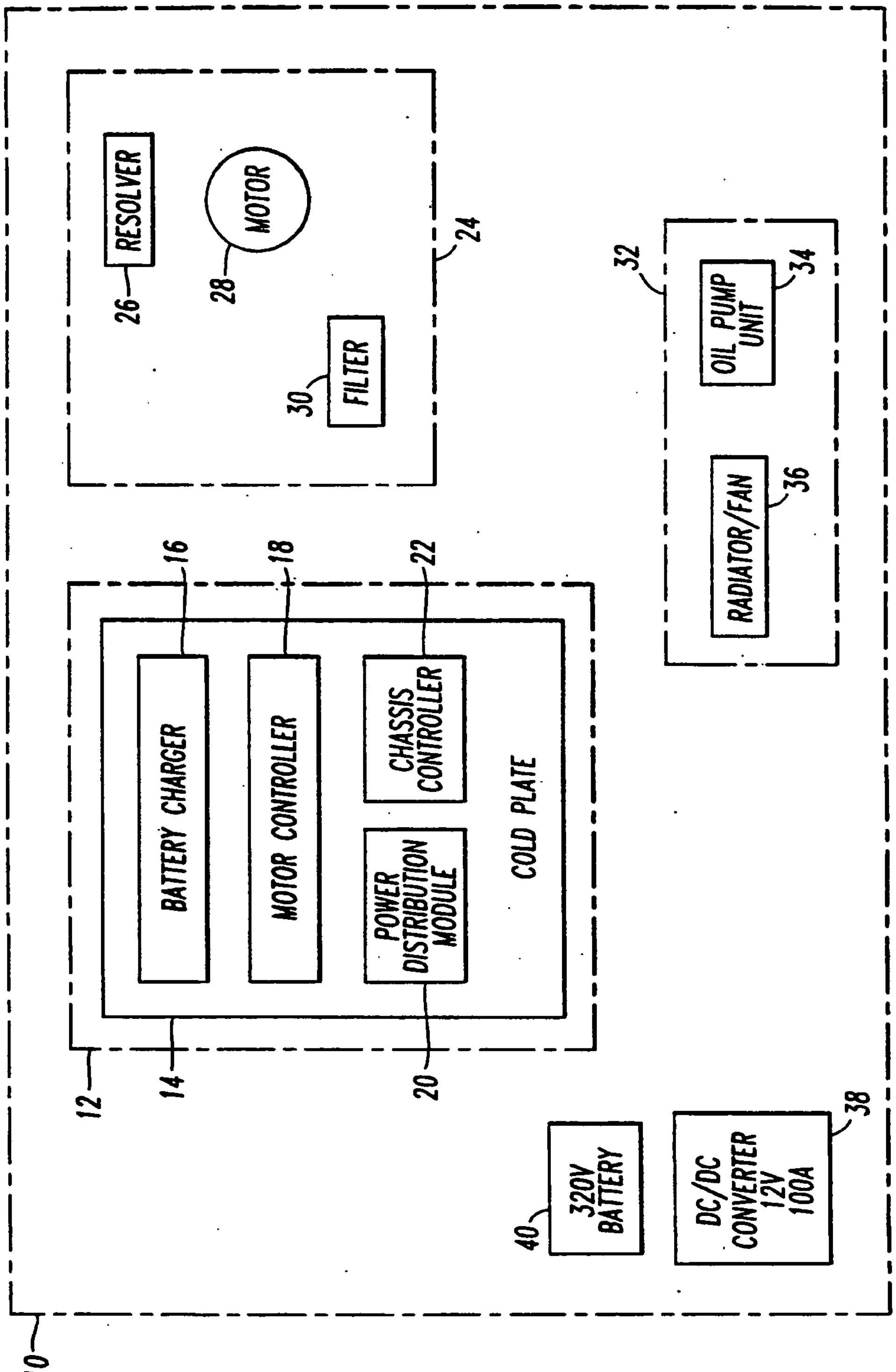
simultaneously drawing the maximum rated current at the second voltage from a secondary winding of the transformer; and

substantially fully charging the capacitor when current is supplied through the primary winding in the first direction and substantially fully discharging the capacitor when current is supplied through the primary winding in the second direction.

9. A method as recited in claim 8, wherein:

the step of alternatingly supplying current comprises supplying current from the battery at the first voltage in a first direction through a series connection of the transformer primary winding and a first capacitor and supplying current from the battery at the first voltage in a second direction through the transformer primary winding and a second capacitor; and

the step of charging and discharging comprises substantially fully charging the first capacitor and substantially fully discharging the second capacitor when current is supplied through the transformer primary winding in the first direction, and substantially fully discharging the first capacitor and substantially fully charging the second capacitor when current is supplied through the transformer primary winding in the second direction.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BATTERY CHARGER
MOTOR CONTROLLER
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COLD PLATE
320V BATTERY
DC/DC CONVERTER 12V 100A
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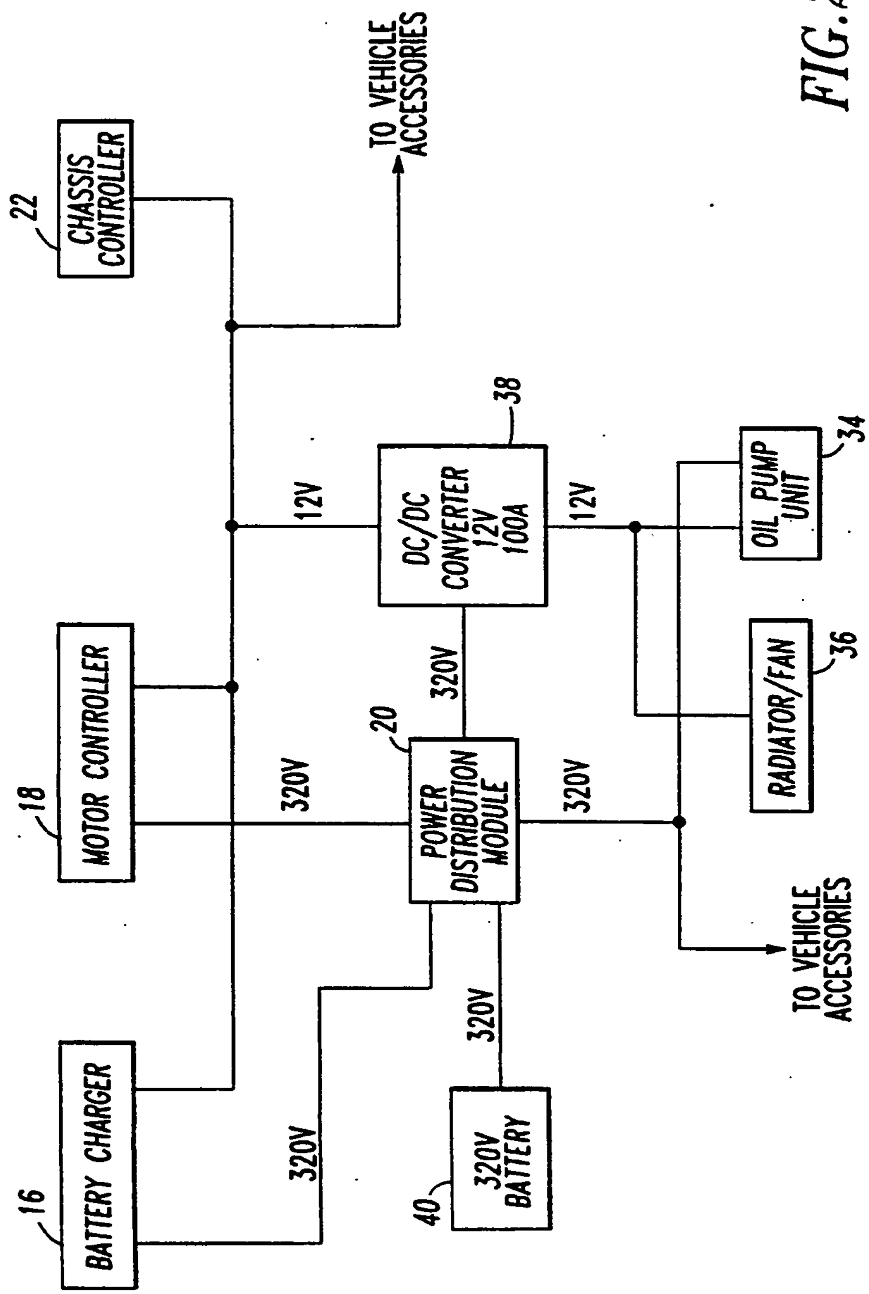
FIG. 1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CHASSIS CONTROLLER
TO VEHICLE ACCESSORIES
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12V
DC/DC CONVERTER 12V 100A
12V
OIL PUMP UNIT
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MOTOR CONTROLLER
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320V
20
POWER DISTRIBUTION MODULE
320V
RADIATOR/FAN
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TO VEHICLE ACCESSORIES
BATTERY CHARGER
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320V
320V BATTERY
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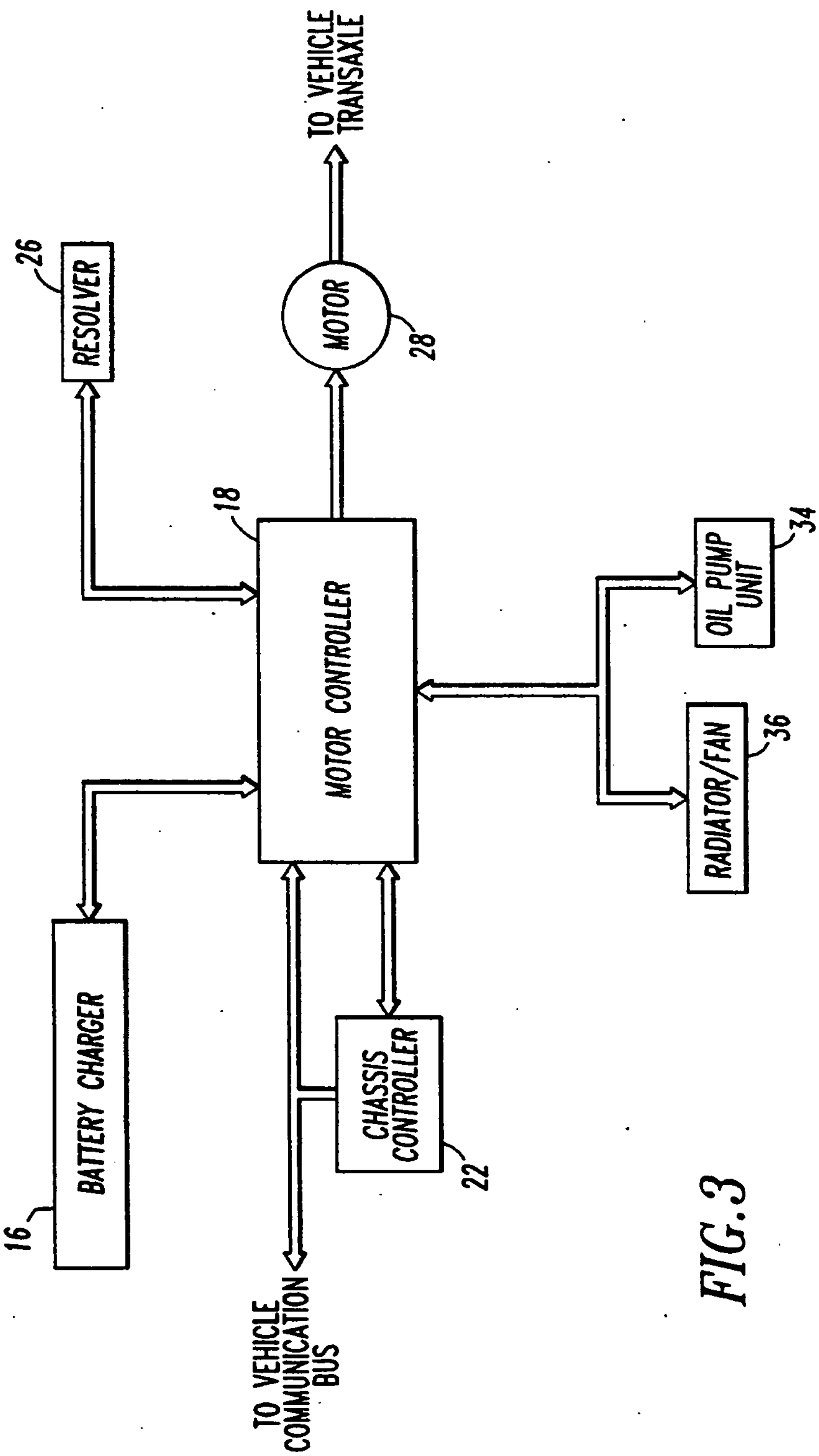
FIG.2


TO VEHICLE TRANSAXLE
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RESOLVER
MOTOR
28
18
MOTOR CONTROLLER
34
OIL PUMP UNIT
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RADIATOR/FAN
BATTERY CHARGER
16
CHASSIS CONTROLLER
22
TO VEHICLE COMMUNICATION BUS

FIG.3

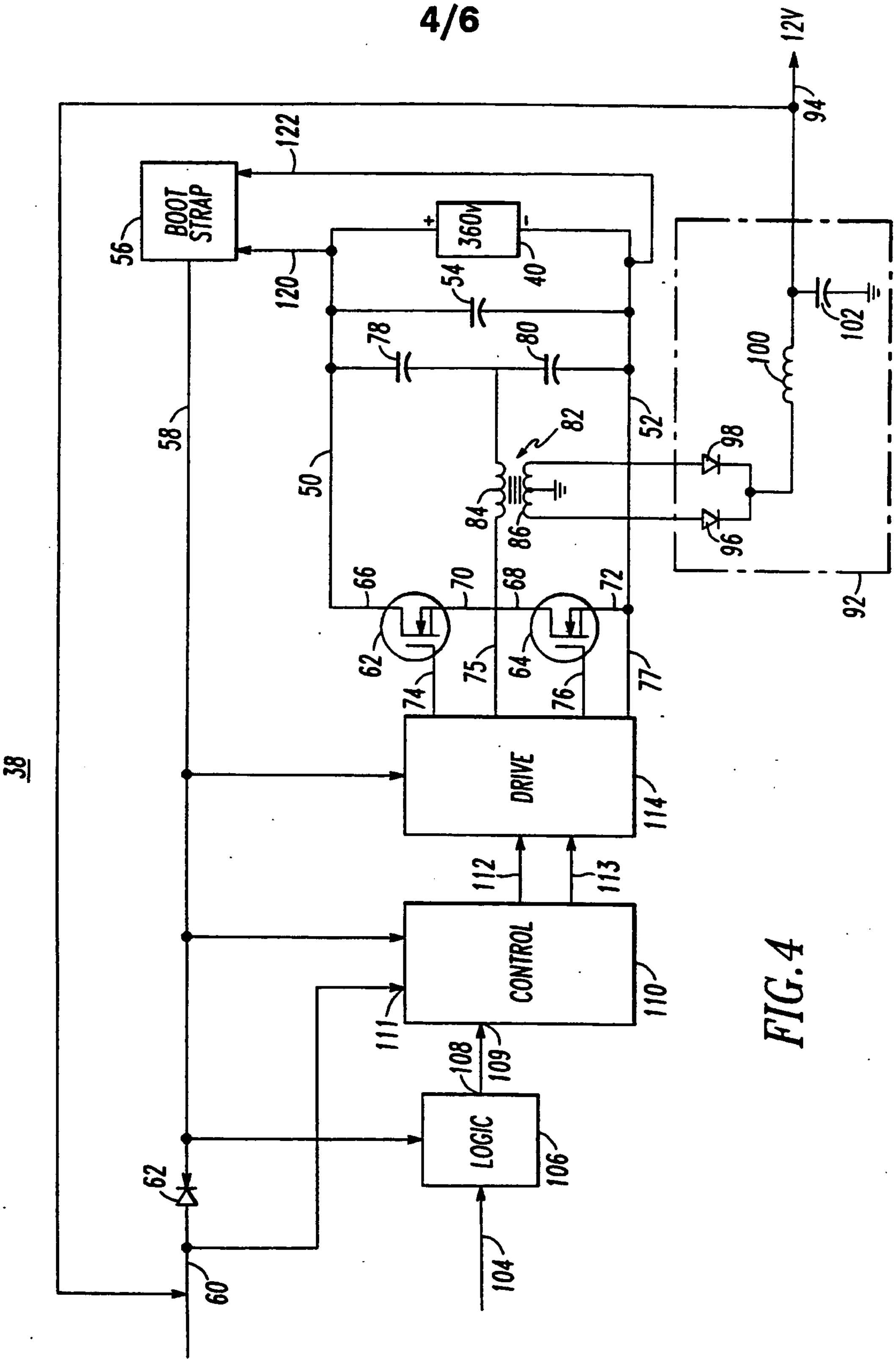

FIG.4

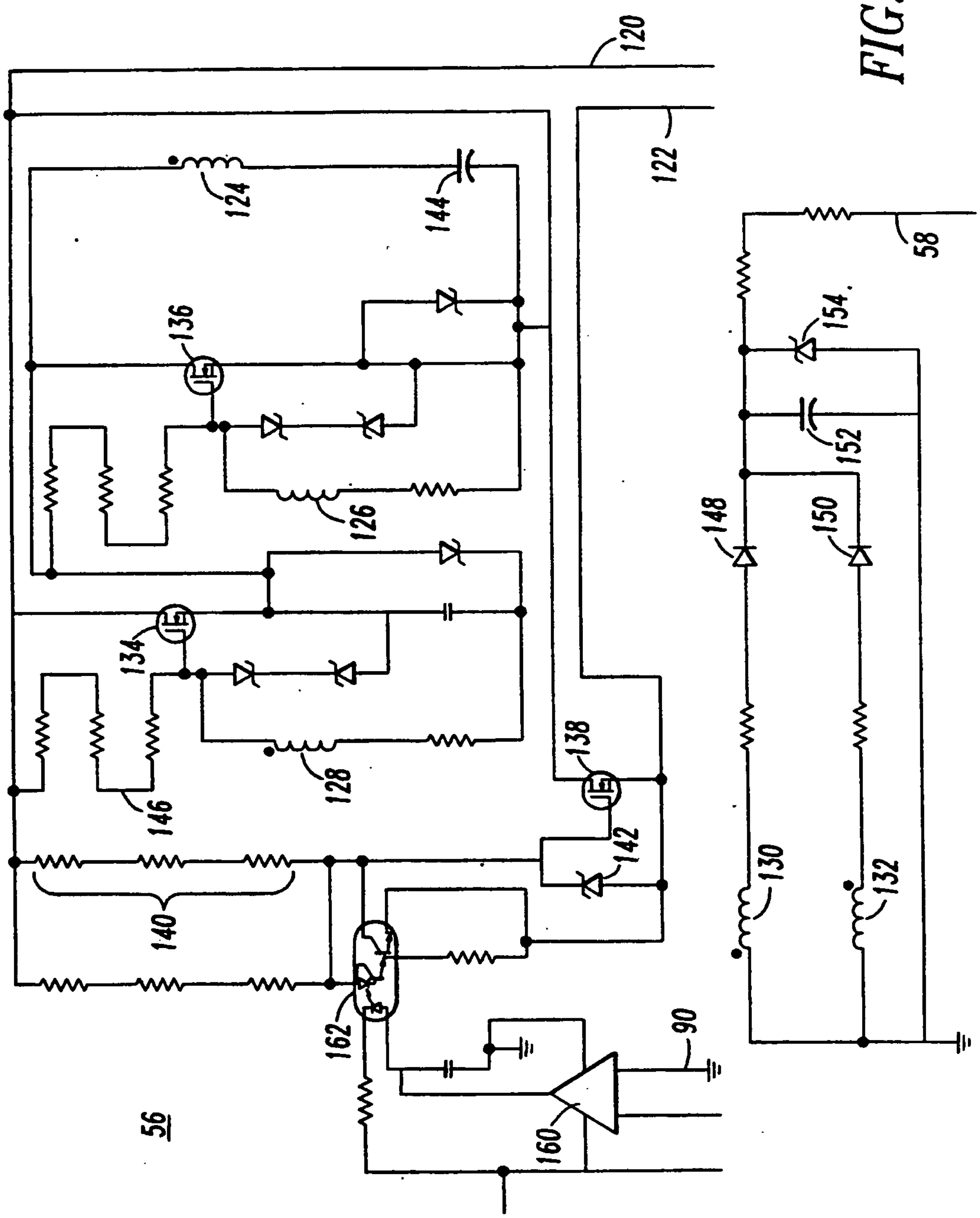
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FIG.5

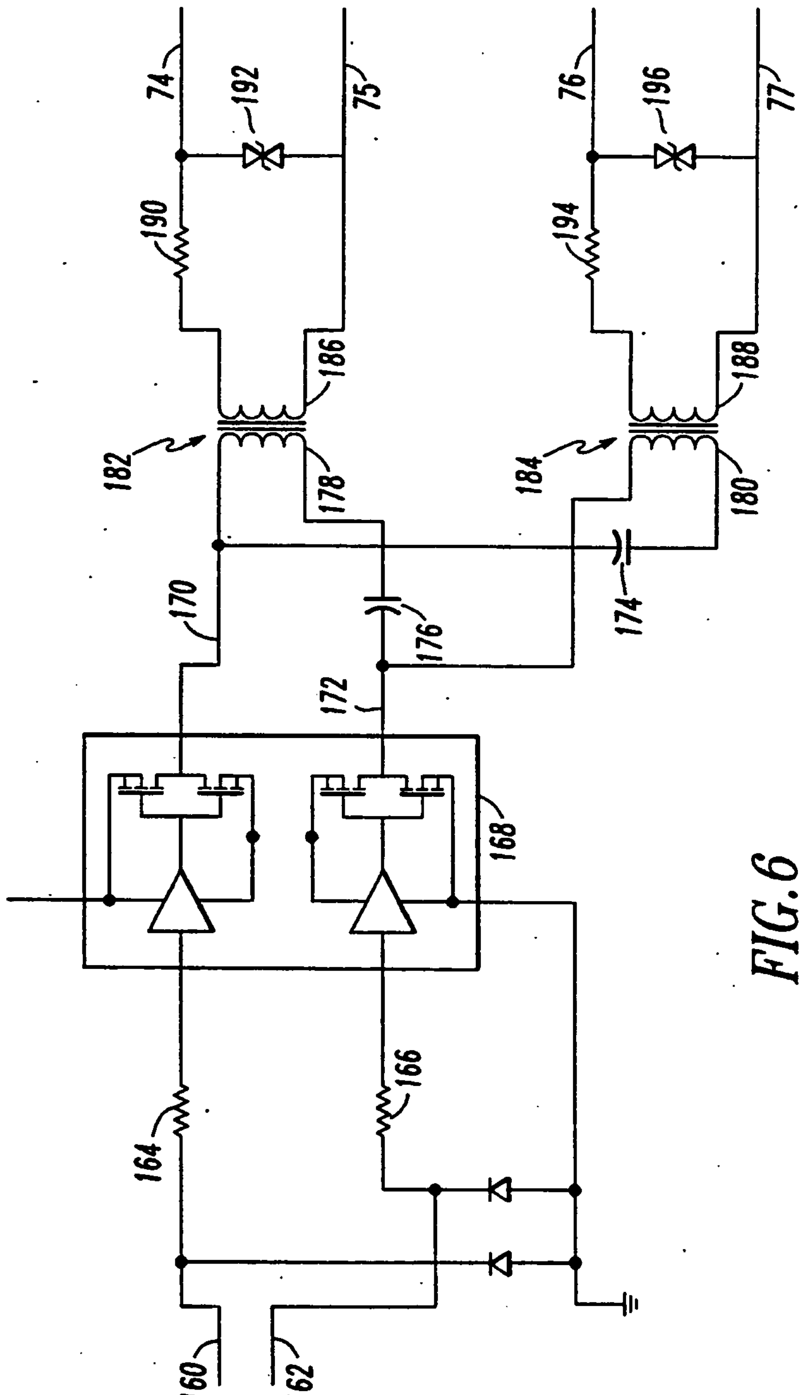
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FIG.6

INTERNATIONAL SEARCH REPORT

In ional Application No
PCT/US 95/07078

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H02M3/337 H02M1/00 B60L1/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H02M B60L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US-A-4 922 397 (HEYMAN ALBERT M) 1 May 1990 see column 4, line 61 - column 5, line 6; figures 1,2,6 see column 6, line 1 - line 7 ---	1,2,8,9
Y	EP-A-0 116 925 (BBC BROWN BOVERI & CIE) 29 August 1984 see page 4, column 31 - page 5, column 22; figure 2 --- -/--	1,2,8,9

[X] Further documents are listed in the continuation of box C. [X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
4 September 1995	13.09.95

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Bourbon, R

Form PCT/ISA/210 (second sheet) (July 1992)

International Application No
PCT/US 95/07078

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PROCEEDINGS OF THE EUROPEAN CONFERENCE ON POWER ELECTRONICS AND APPLICATIONS. (EPE), AACHEN, 9 - 12 OCTOBER, 1989, vol. 3, 9 October 1989 LEONHARD W;HOLTZ J; SKUDELNY H C, pages 1455-1459, XP 000143576 VAN DER BROECK H ET AL 'A COMPACT HIGH PERFORMANCE 300 W/5 V SWITCHED MODE POWER SUPPLY' ---	1-4,8,9
A	US-A-4 717 867 (FOREHAND GILBERT H) 5 January 1988 see abstract ---	5-7
A	FR,A,2 694 144 (ENERTRONIC SA) 28 January 1994 see page 9, line 7 - line 18 -----	

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 95/07078

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-4922397	01-05-90	NONE	
EP-A-0116925	29-08-84	DE-A- 3305224	16-08-84
US-A-4717867	05-01-88	NONE	
FR-A-2694144	28-01-94	NONE	